DEPARTMENT OF SCIENCE
BUREAU OF METEOROLOGY

TECHNICAL REPORT 4

THE PREDICTION OF RADIATION FOG CLEARANCE

R.D. Hoy

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THE PREDICTION OF RADIATION FOG CLEARANCE

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ABSTRACT

A method for predicting the clearance of radiation fog by radiation budget considerations is developed for the southern half of Australia. Tables of net radiant energy available to evaporate a fog are presented for latitudes 30°S, 35°S and 40°S by hour of day for each month of the year. For 20 fogs at Laverton, Victoria and 54 fogs at Wagga Wagga, New South Wales the predicted clearance times had a standard deviation of approximately 40 minutes about the observed clearance times using radiosonde data. The mean difference between observed and predicted clearance times was zero at Wagga Wagga. For Laverton and Canberra the mean predicted clearance times were late by half an hour and one hour respectively.

INTRODUCTION

Fog formation at aerodromes is a continuing difficulty for airline operators and weather forecasters. It is usually possible to forecast nights when fog is likely to form but the prediction of the exact time of formation is still very difficult owing to insufficient knowledge of the physical processes involved. Given that a fog has formed, a further forecast is required of the expected time of clearance of the fog. Relatively little attention seems to have been given to this problem compared to that given to forecasting the time of fog formation, a more complicated process. An accurate forecast of the clearance time for radiation fog would enable more efficient resumption of airline schedules from such cities as Canberra and Launceston where winter fogs often persist for the whole morning.

Kennington (1961) has shown how radiation fog clearance may be forecast by considering the total radiant energy available to evaporate the fog. Barthram (1964) has produced three diagrams based on Kennington (1961) which enable the clearance time of fog to be determined more easily. A number of trials have been conducted using the method of Kennington (1961) in England (Atkins, 1965; Heffer, 1965 and Jennings *et al*, 1965). These showed that the predicted clearance times were within ±½ hour of the true clearance times for about 50% of cases and within ±1 hour in about 75% of cases, varying somewhat with the different locations considered. They comment that corrections to the clearance times may be required depending on the contribution of advection at the various sites. Adamy (1967) in Hungary and Kagawa (1967) in Canada have also obtained similar accuracies in predicting radiation fog clearance based on Kennington (1961). Wright and Weinman (1967) have used a photocell on a balloon to determine fog depth and obtained a 2 hour predicted clearance time within 10 minutes of the true clearance time. All the above references used the radiant energy tables of Kennington (1961) which are applicable for latitude 50°N only. This paper describes the calculation of radiant energy tables applicable for latitudes from 30°S to 40°S in Australia and the testing of these for 3 Australian locations.

METHOD

(a) Radiation balance at the top of the fog

In order to calculate the net radiant energy available to clear a fog, it is necessary to consider the radiation balance at the top of the fog after sunrise. If F is the net flux of radiant energy at the top of the fog (considered positive downward) then, on a horizontal surface;

$$F = J + D - R - B \qquad \ldots 1$$

where J is the direct beam insolation depleted by passage through the atmosphere, D is diffuse or sky radiation resulting primarily from scattering of solar radiation, R is the quantity of J + D reflected from the top of the fog and B is the net long-wave flux upward from the top of the fog. Of the terms in Eq 1, J is usually the largest with R proportionately smaller. D and B are typically of the same order of magnitude and smaller than R and J, except for large zenith angles where all the

terms are of similar magnitude, making F very sensitive to small inaccuracies in any of the above components.

The total radiant energy I(t) which is absorbed by the fog after sunrise, up to a given time of the day t, is given by;

$$I(t) = \int_{\text{sunrise}}^{t} F \, dt \qquad \ldots 2$$

The dependence of the terms on the right hand side of Eq 1 on the season and hour of day will now be determined to enable the calculation of I(t).

(b) Direct beam insolation

The flux of solar radiation, normal to the solar beam incident on the top of the atmosphere when the earth is at its mean distance from the sun, is known as the solar constant S_o. Drummond (1971) has reviewed many previous measurements of S_o and his mean value of 1353 Wm^{-2} (1.940 cal cm^{-2} min^{-1}) with an error estimate of 1% has been used in this paper. The flux of solar radiation S at the top of the atmosphere varies with the seasonal change of the distance between the sun and the earth, thus;

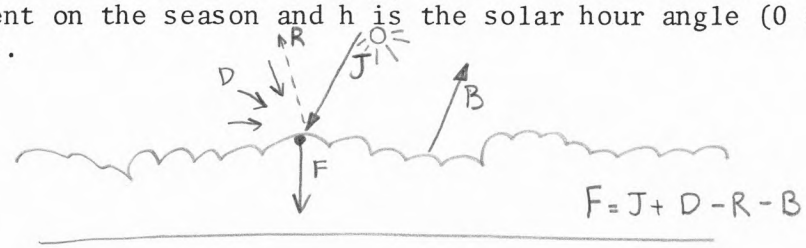
$$S = \frac{S_o}{r^2} \qquad \ldots 3$$

where r is the distance of the sun from the earth measured in units of the mean sun-earth distance.

The flux of solar radiation on a horizontal surface at the top of the atmosphere decreases in proportion to the cosine of the zenith angle z of the sun. The zenith angle of the sun is given by;

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos h \qquad \ldots 4$$

where ϕ is the station latitude, δ is the sun's declination, dependent on the season and h is the solar hour angle (0 at midday).



The relationship between h in radians and time of day t in hours (True Solar Time) is;

$$h = \frac{\pi(t-12)}{12} \qquad \ldots 5$$

If we also consider an atmosphere with zenith transmission coefficient q, then transmission decreases as the zenith angle increases according to Beer's Law. The flux of solar radiation normal to the surface of the earth, allowing for the effects of absorption in the atmosphere, is known as the depleted insolation and is given by;

$$J = \frac{S_o}{r^2} q^{\sec z} \cos z \qquad \ldots 6$$

where z may be determined for any time of day from Eq 4 and 5.

In order to simplify the computation of J, a mean atmospheric transmission $\bar{q}$ averaged over time of day and the seasons was derived so that Eq 6 becomes;

$$J = \bar{q} \frac{S_o}{r^2} \cos z \qquad \ldots 7$$

Gold (1933) assumed $\bar{q}$ equals 0.50 for latitude 50^{o}N. This corresponds to $\bar{q}$ equal to 0.58 for latitude 40^{o}S and to 0.62 for latitudes 35^{o}S and 30^{o}S. These values were used in this study. For the assumption of the use of a single yearly average of $\bar{q}$ for a given latitude to be realistic for all seasons, it is required that q varies with the seasons, being greatest in winter when mean atmospheric paths are longest and least in summer when mean atmospheric paths are shortest. This is generally true. The use of a single yearly average $\bar{q}$ at each latitude, for all seasons and times of day, ignores variations in q due to all factors except the increase in daily average zenith angle with increasing latitude.

After substituting Eq 4 and 5 in 7, a numerical integration was performed to evaluate the radiant energy due to direct beam insolation I_J (t) where;

$$I_J(t) = \int_{\text{sunrise}}^{t} J \, dt \qquad \ldots 8$$

Tables of I_J (t) were calculated for each hour of the day, for the 23rd day of each month and for latitudes of 30°S, 35°S and 40°S. The values for δ and r were from List (1966).

(c) Diffuse radiation

Schüepp (1966) gives a graphical method for calculating diffuse radiation when the albedo of the underlying surface α, the zenith angle z, the precipitable water vapour w and the turbidity β are known. From Pierrehumbert (1972), a mean w of 1 cm was deduced for clear sky conditions over continental locations with latitudes between 30°S and 45°S. Robinson (1966) gives a mean turbidity of 0.1 for similar latitudes. For these mean atmospheric conditions, D was calculated for various z with $\alpha = 0.25$ (bare ground) and $\alpha = 0.5$ (mean fog bank). The results are shown in Fig 1. Varying w from 1 to 2 cm made no difference to D whereas varying α from 0.25 to 0.5 increased D by up to 25%. The variation of albedo with zenith angle (Paltridge and Sargent, 1971) was not considered to be a significant effect for these calculations.

In order to simplify the numerical integration of the contribution of D to the right hand side of Eq 2, the curves of Fig 1 were fitted by a polynomial series in cos z. Thus for $\alpha = 0.25$;

$$D_{0.25} = - 0.09729 + 208.60\ x + 43.923\ x^2 - 81.38\ x^3 \ (W\ m^{-2}) \quad \ldots 9$$

and for $\alpha = 0.5$

$$D_{0.5} = 0.3183 + 205.15x - 32.184x^2 - 39.131x^3 \ (W\ m^{-2}) \quad \ldots 10$$

where $x = \cos z$.

The mean deviation of the fitted curves from the original ci curves was about 1% of the maximum D, except for cos $z \simeq 1$ where the error increases to about 2%.

(d) Consistency of direct and diffuse radiation determination

Using the above typical values of β and w, we may estimate a mean daily transmission coefficient $\bar{q}$ for the direct solar radiation for comparison with the values inferred earlier on the basis of Gold (1933). From Zillman (1969), the spectral zenith transmission coefficient for aerosol and molecular scattering $(q_{am})_\lambda$ can be approximated by:

$$(q_{am})_\lambda = e^{-(0.00897\lambda^{-4.09} + \beta\lambda^{-1.3})} \quad \ldots 11$$

where λ is the wavelength in microns. A weighted average of Eq 11 over the solar spectrum with β =0.1 gives;

$$q_{am} \simeq 0.75$$

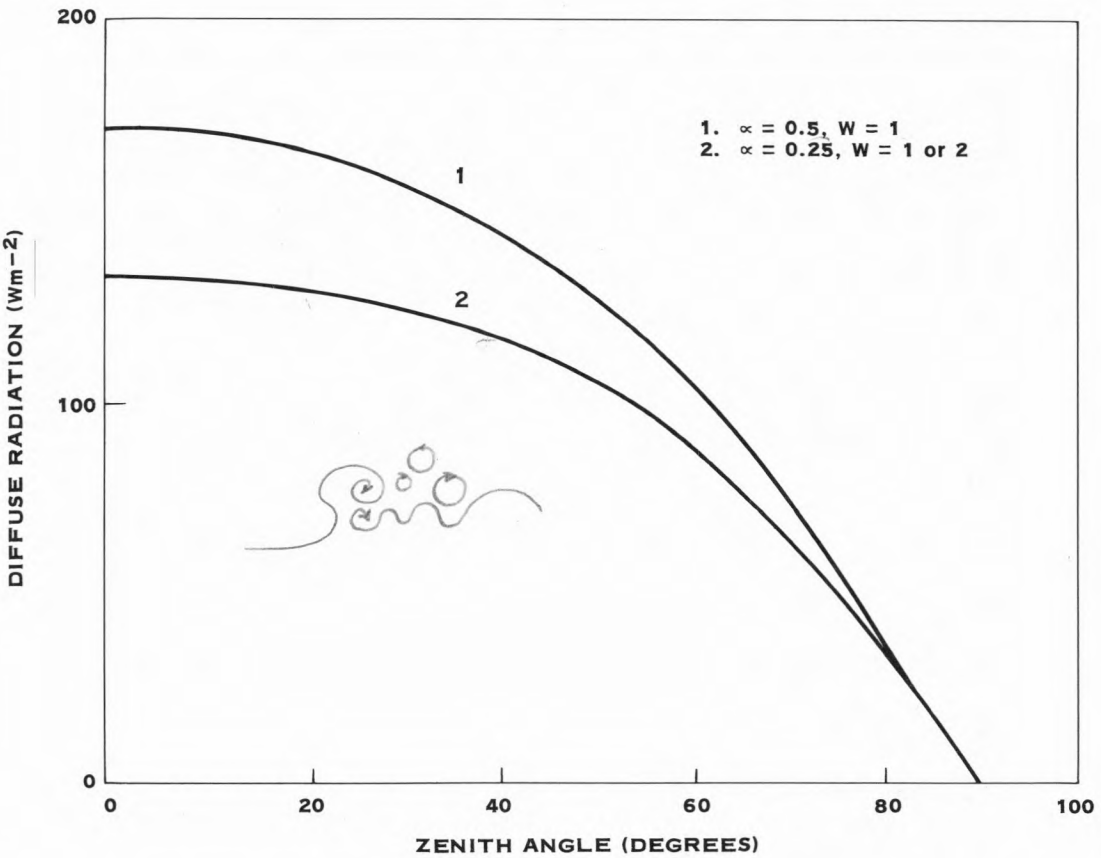


Fig 1 The diffuse radiation (Wm^{-2}) for mean atmospheric conditions as a function of zenith angle z for stated albedo ∝ and water vapour quantity w.

From Mugge and Möller (1932), the mean zenith transmission coefficient due to water vapour absorption may be deduced to be;

$$q_w \simeq 1 - \frac{0.17}{1.94} w^{1/3} \quad \ldots 12$$

For w = 1 cm, $q_w \simeq 0.91$. Thus the zenith atmospheric transmission coefficient, allowing for both scattering (molecular and aerosol) and absorption (water vapour), is given by;

$$q \simeq q_w . q_{am} \simeq 0.68$$

Such a zenith transmission coefficient would give a mean daily transmission coefficient averaged over the year, of about 0.55. This is in reasonable agreement with values adopted in the previous section for $\bar{q}$ of 0.58 and 0.62. It suggests that the D adopted in this study may be up to 10% too large by comparison with the D appropriate to the mean atmosphere adopted in calculating J. However, as J is much larger than D in magnitude, this error is negligible compared to the effects of atmospheric change in w and β.

(e) Reflection from fog

Kennington (1961), based on Hewson (1943), uses 0.4 and 0.6 as average albedos for thin and thick fog respectively. As these values appear reasonable they were adopted for this study. A thick fog has a visibility of less than 550 m whereas a thin fog has a visibility of between 550 and 1000 m. As R is generally much larger than D, sufficient accuracy in the determination of D was obtained by assuming a mean albedo for thick and thin fogs of 0.5.

(f) Long-wave radiation

The earth emits long-wave radiation according to the Stefan-Boltzmann Law dependent on the surface temperature T_s. The atmospheric gases, water vapour, carbon dioxide and ozone also emit long-wave radiation, part of which is received at the earth's surface. The rate of cooling of the earth's surface is dependent on the effective radiation B, the difference between the upward flux from the ground and the downward atmospheric flux. Where a well developed fog covers the ground, the downward long-wave radiation from the fog droplets reduces the radiation flux divergence at the earth's surface and thus reduces the cooling rate. The region of maximum long-wave radiation flux divergence is now near the top of the fog layer which radiates approximately as a black body. The temperature profile within the fog tends towards isothermal and the upper

surface of the fog becomes the region of maximum radiative cooling. It thus follows that the upward long-wave radiation from the upper surface of the fog may be estimated by assuming that the temperature of the top of the fog is approximated by the minimum air temperature in the screen. This temperature was estimated from the "Climate of Australia and Papua-New Guinea, 1971" by using the mean monthly minimum temperatures for cities with appropriate latitudes. For 40^{o}S, the average of Hobart and Melbourne mean monthly minimum temperatures was used to estimate upward radiative fluxes for each month of the year. For 35^{o}S and 30^{o}S, the appropriate mean minimum temperatures for Canberra and Sydney respectively were employed. These temperatures vary from 0^{o} to 15^{o}C for the months when fogs are most likely.

The evaluation of B was approached by considering the effective emissivity ε_e of the top of the fog, defined as;

$$\varepsilon_e = \frac{B}{\sigma T^4} \qquad \ldots 13$$

where σ is the Stefan-Boltzmann constant (5.7×10^{-8} W m^{-2} K^{-4}). Kondratyev (1969) has summarised experimental studies of ε_e with clear skies which suggest that ε_e decreases with increasing water vapour pressure. Staley and Jurica (1972) also show a similar variation. Swinbank (1963) has derived an empirical relation between ε_e and T which exploits the observed close correlation between vapour pressure and temperature to supress vapour pressure as an independent variable in effective radiation calculations. His relationship, in fact, implies near constancy of B with temperature over the range 0^{o} to 15^{o}C. However, in line with Gold (1933), the values of B used in this study are derived by assuming a constant value of 0.3 for ε_e. As B is generally less than J, the assumptions used to determine B, will not introduce large errors in F.

(g) Radiant energy tables

The radiant energy calculated using Eq 2 for latitudes 30^{o}S, 35^{o}S and 40^{o}S are shown in Table 1, 2 and 3. These tables describe the total radiant energy (J m^{-2}) available to clear thick fog banks (visibility less than 550 m) but they may not be used without modification over other surfaces as they would need to be corrected for the effects of surface albedo and evaporation at the surface. For a thin fog bank, (visibility between 550 m and 1000 m), Kennington (1961) increased the available radiant energy by 50% to allow for

reduced reflection and his procedure has been followed in this paper to calculate clearance times. It is recognised that a more rigorous treatment of radiation mentioned previously is possible but it is considered that the accuracy attained in Tables 1, 2 and 3 is sufficient for this application. The overall consistency of the radiant energy tables for winter months with observations is demonstrated later in the test cases performed.

The determination of F in Eq 1, immediately after sunrise, sometimes resulted in small negative values. Although some negative values after sunrise could be expected, it was felt that they were mostly due to the effect of the approximations assumed in determining the terms on the right hand side of Eq 1. In these cases, F was set equal to zero. It was assumed after Gold (1933) that the maximum temperature for the day would normally occur by 1500 hr and so the tables were not continued beyond this time.

Table 1 Total radiant energy (10^4J m^{-2}) available to clear a thick fog at 30°S for the 23rd day of each month up to a given hour of the day. For a thin fog, the total radiant energy should be increased by 50%.

True Solar Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0700												
0800	33	17	1						8	25	38	50
0900	121	92	63	29	13		13	33	71	105	126	142
1000	234	197	151	96	63	42	67	105	159	213	243	259
1100	368	318	259	188	134	109	138	193	272	339	377	389
1200	507	452	377	285	218	180	222	293	393	469	511	527
1300	645	578	498	385	297	251	301	393	511	603	649	670
1400	774	703	607	473	368	314	372	486	624	728	783	804
1500	887	808	695	544	419	377	427	557	716	837	896	921

	J	F	M	A	M	J	J	A	S	O	N	D
ASSY MIN	65	65.2	63.2	58.0	52.2	48.4	46.1	47.7	51.4	55.9	59.6	62.9
ASCB MIN	54.9	54.4	50.5	43.6	36.8	33.7	31.7	33.4	36.9	42.3	46.6	51.9
MEAN °C												

Table 2 Total radiant energy (10^4J m^{-2}) available to clear a thick fog at 35°S for the 23rd day of the month up to a given hour of the day. For a thin fog, the total radiant energy should be increased by 50%.

True Solar Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0600												
0700										2	4	13
0800	54	38	4						8	46	63	75
0900	147	113	63	29				38	75	130	155	172
1000	259	213	151	92	46	42	50	101	159	234	272	289
1100	393	335	255	176	109	96	113	184	268	360	406	427
1200	532	465	368	268	180	159	184	281	385	494	557	565
1300	670	594	486	360	255	232	259	377	502	624	689	712
1400	799	716	590	444	318	281	322	461	611	745	821	846
1500	917	816	674	507	364	339	368	523	699	854	938	963

Table 3 Total radiant energy (10^4J m^{-2}) available to clear a thick fog at 40°S for the 23rd day of each month up to a given hour of the day. For a thin fog, the total radiant energy should be increased by 50%.

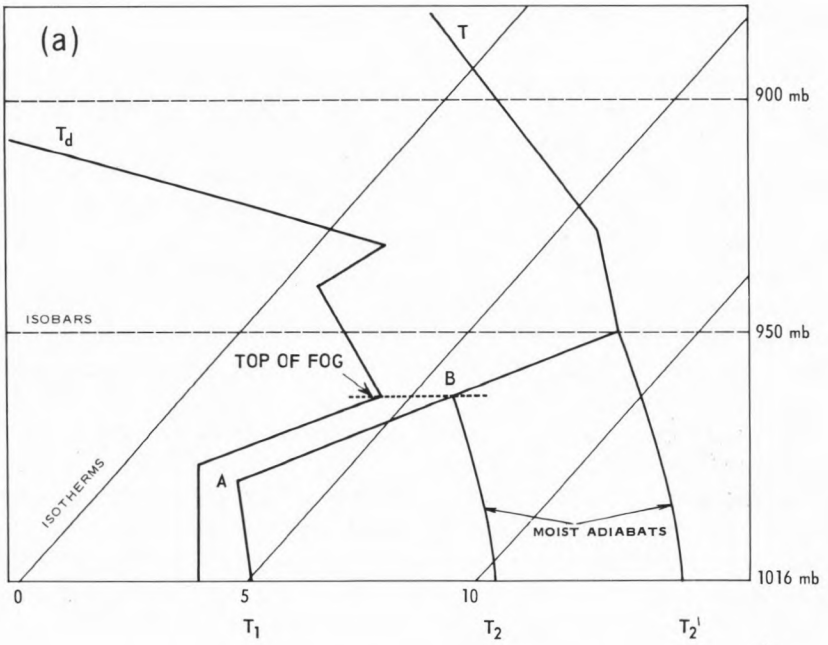
True Solar Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0600												
0700	17										21	17
0800	84	42	4						13	50	92	92
0900	188	126	67	8				33	71	138	199	201
1000	318	239	159	71	21	13	21	92	163	255	322	335
1100	465	377	272	155	79	63	79	176	272	389	473	486
1200	619	511	389	247	147	117	147	268	393	536	628	641
1300	766	653	511	339	213	172	213	360	515	678	783	799
1400	921	783	619	419	268	218	272	452	628	812	929	950
1500	1051	896	712	481	306	247	310	507	720	929	1059	1084

(g) Calculation of clearance time

In order to calculate the clearance time using Table 1 to 3, it is necessary to calculate the energy required to clear the fog. This is dependent on the temperature structure of the fog, initially and at clearance. The two commonly observed temperature structures are shown schematically in Fig 2(a) and 2(b) as obtained from the 2300Z radiosonde data. For the Laverton data used, 60% conform to the general structure of Fig 2(a) and the remainder to that of Fig 2(b). For the Wagga Wagga data, the percentages are 75 and 25 respectively. To determine the energy required to clear the fog, a temperature structure at clearance must be adopted. Kennington (1961) suggested that the initial (dawn) screen temperature T_1 in the fog increases to a temperature T_2' at clearance such that a saturated adiabatic lapse rate has been established between the ground and the top of the temperature inversion associated with the fog (see Fig 2(a) and 2(b)). Heffer (1965) suggests that clearance occurs when a saturated adiabatic lapse rate is established between the ground and the top of the fog, indicated by the top of inversion in the dew point temperature or by the height at which the dew point and dry bulb temperature profiles begin to diverge. This gives a clearance temperature T_2 (Fig 2(a) and 2 (b)) which is less than T_2' since the top of the temperature inversion is usually above the top of the fog (Rodhe, 1962). T_2 has been used in this paper as the forecast clearance temperature.

Where the fog temperature structure is known, it is plotted on a skew T-log P aerological diagram (F160). Also plotted on the diagram is the saturated adiabatic profile from the top of the fog which represents the temperature structure when the fog has cleared. The area between the two dry bulb traces on this chart is proportional to the energy (H) required to heat the air and water vapour from the initial to the final states. The constant of proportionality was found to be 1.93×10^6 J m^{-2} (46 cal cm^{-2}) for each cm^2 of area on this chart.

Where the fog temperature structure is not known, it is necessary to estimate from climatological or other considerations the fog depth (d), the clearance temperature (T_2) and a mean temperature profile from the ground to the fog top. The field trials referenced in the introduction give various methods of estimating these quantities and suggest that provided each location is considered individually, adequate accuracy can be obtained for predicting fog clearance without a temperature sounding for each fog. For a fog temperature



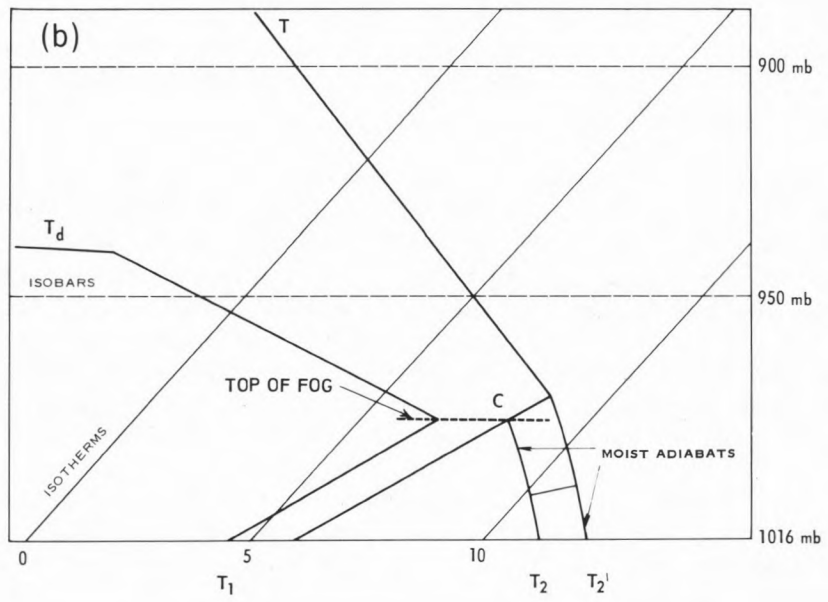


Fig 2 (a) and (b) show schematically the two most commonly found temperature profiles for radiation fog as determined from radiosonde data for Laverton and Wagga Wagga. Proposed clearance temperatures T_2 and T_2^1 are discussed in the text.

profile as shown in Fig 2(a), as described by Kagawa (1967),

$$H = 8.17 \times 10^3 \ (T_2 - T_1) \ d \qquad (J\ m^{-2}) \qquad \ldots 14$$

For the temperature profile of Fig 2(b), as described by Kennington (1961),

$$H = 5.1 \times 10^3 \ (T_2 - T_1) d \qquad (J\ m^{-2}) \qquad \ldots 15$$

where T_1 and T_2 are measured in ^{o}C and d is in mb.

Having calculated the energy H required to heat the air and water vapour to the clearance temperature profile, additional heat is required to heat and evaporate the fog droplets. Kennington (1961) has derived a correction factor K which when multiplied by the energy H required to heat the air and water vapour to clearance gives the total energy required for fog clearance.

$$K \simeq 0.03 \ (T_1 + T_2) + 1.7 \qquad \ldots 16$$

where T_1 and T_2 are measured in ^{o}C. When the product of H and K is known, the clearance time for the fog may be found by reference to the radiant energy tables for the station latitude and month of the year, Tables 1, 2 and 3. Barthram (1964) has devised a graphical method based on the tables of Kennington (1961) which enables the clearance time to be calculated rapidly where d, T_1 and T_2 are known for both thick and thin fogs.

The clearance times obtained using Table 1, 2 and 3 are in terms of True Solar Time (TST) *ie*, the time determined by the position of the true sun overhead at the particular station. Where a forecast is required in Local Standard Time (LST) *ie*, the time determined by the position of the mean sun relative to the mean longitude of the time zone, the equation relating TST and LST is;

$$LST = TST - E - Z \qquad \ldots 17$$

where Z is dependent on the station longitude and E is the value of the equation of Time which varies with the day of the year (List, 1966). Z may be up to ±30 minutes for a given station and E varies through the year by±16 minutes. All observed clearance times have been converted from Local Standard Time to True Solar Time using Eq 17 for comparison with predicted clearance times in this paper.

RESULTS

In order to evaluate the method for predicting fog clearance, fog days for the period 1967 to 1972 were chosen for stations where 2300 GMT radiosonde flights are made. The radiosonde temperature profiles give the fog height and clearance temperature from which the prediction is made. Days where fog was patchy were eliminated as the clearance time was uncertain and the radiosonde data likely to be unrepresentative. Also, days on which fog cleared before 0900 EST were eliminated. The times between which fog clearance occurred were obtained from the Aerodrome Meteorological Reports (Form A4 or A37) and the clearance time taken as the midpoint of this time interval. The observed fog clearance time usually has an error of about ±30 minutes. Predicted clearance times using the radiant energy tables considered heat absorbed after 0900 EST rather than dawn. Suitable data were obtained for Laverton, Victoria (latitude 37° 52'S, longitude 144° 45'E, altitude 15 m) and Wagga Wagga, New South Wales (Latitude 35° 09'S, longitude 147° 29'E, altitude 234 m). Some fog data were also obtained for Canberra (latitude 35° 18'S, longitude 149° 11'E, altitude 617 m).

(a) Laverton

Fog data were obtained for 20 suitable days in the months of February, May to August and October and the results of predictions of fog clearance are shown in Fig 3 using Table 3 for latitude 40°S. The distribution of the difference between the predicted and observed clearance times (in True Solar Time) is shown in Fig 4. The mean of the distribution occurred at +30 minutes *ie*, the mean prediction was 30 minutes too late and the standard error was 38 minutes about the mean. There were two consecutive days where fog lasted all day whereas the prediction suggested clearance should occur before midday. On one of the days some middle level cloud was suspected from the radiosonde trace. There was no obvious cause for the other failure but this does show the need to check on other meteorological processes outside the scope of the above prediction scheme which will prevent its successful operation.

As Laverton is situated almost midway between latitude 35°S and 40°S, the predicted clearance times were recalculated using Table 2 for latitude 35°S for the same data. The mean predicted time was now 7 minutes late with a standard error of 41 minutes. This suggests that the predictions are

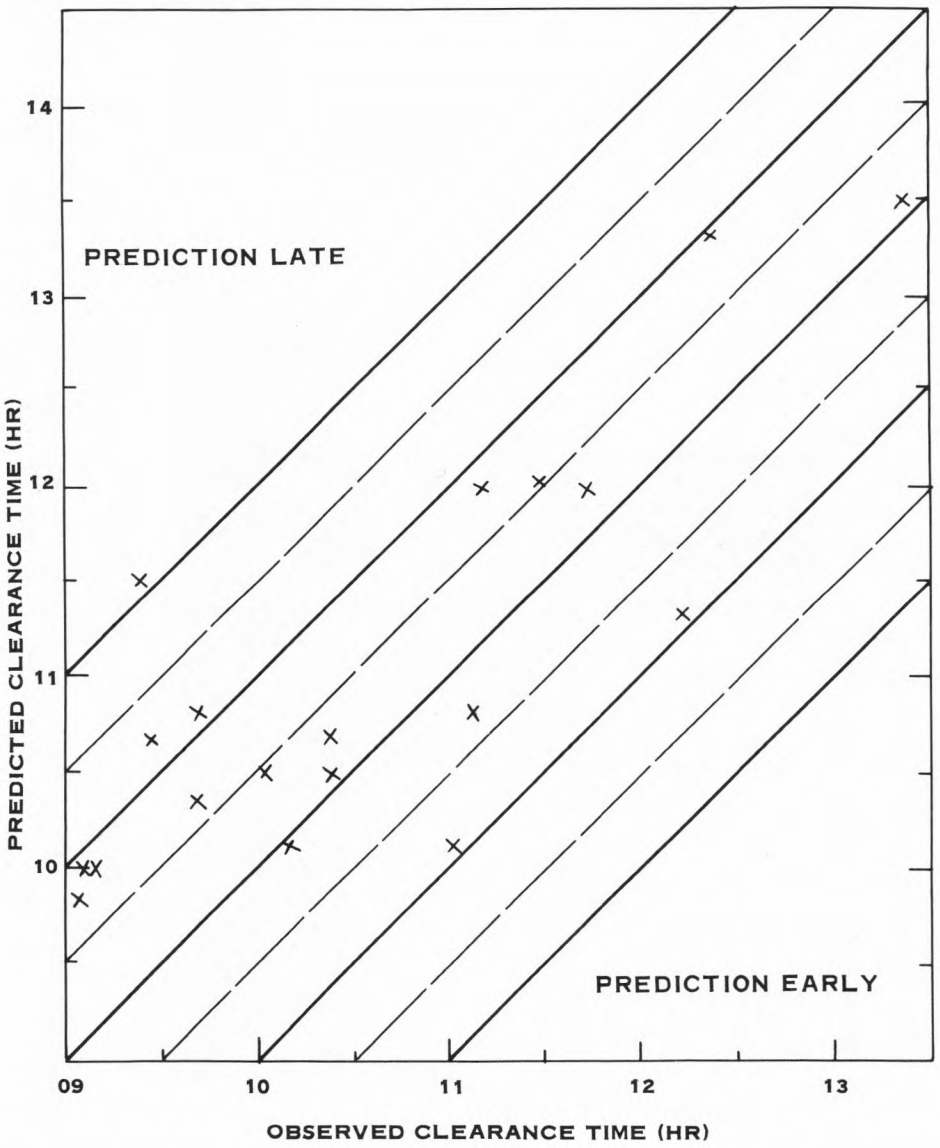


Fig 3 The predicted clearance times based on radiosonde data for 20 cases of fog at Laverton, Victoria plotted against the observed clearance times. All times are in true solar time.

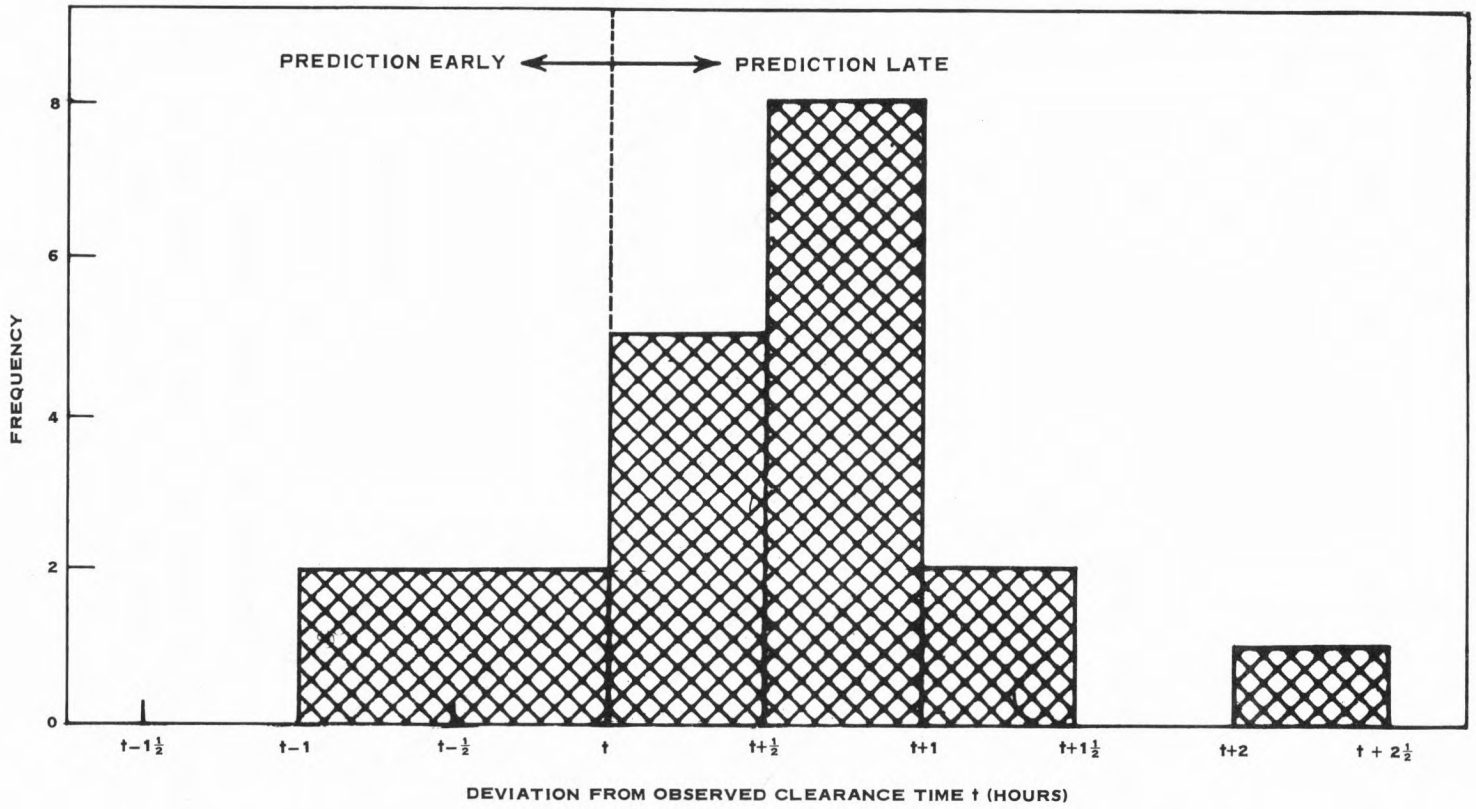


Fig 4 Histogram showing the frequency distribution of the difference between predicted and observed clearance times (hr) for Laverton data of Fig 3.

slightly more accurate using Table 3 but that either Table 2 or 3 could be used provided that the Table 3 prediction time be reduced by 30 minutes.

(b) Wagga Wagga

Fog days were selected as above and 55 suitable days were found covering the months April to September. The agreement between predicted and observed clearance times is shown in Fig 5 for 54 cases. On 15 July 1968 fog lifted to form low stratus which persisted during the day. The surface visibility improved from 800 to 1500 yd (730 to 1370 m) between 0900 and 1200 EST whereas the predicted clearance time was 1100 EST. The mean prediction time was found to be 3 minutes late with a standard error about the mean of 40 minutes similar to Laverton. The distribution of the difference between the predicted and observed clearance times is shown in Fig 6.

Another case of fog lasting all day was on 23 June 1970, not included in 55 cases above. In this case some high cloud was reported when the fog thinned in the afternoon and also appears on the radiosonde trace of 24 June 1970. The effect of high cloud is to decrease the direct beam insolation and thus the total radiant energy at the fog top. This was the only case where high cloud was observed in association with fog. Wright and Weinman (1967) have developed an instrument to detect high cloud which could be employed if high cloud was found to be a serious problem at any particular site. The agreement of the mean prediction time within 3 minutes of the observed times suggests that the energy tables and the prediction scheme give consistent results. Eldridge (1972) gives a relationship between liquid water content and the visibility of fog. For Wagga Wagga, the correlation between dawn visibility and liquid water content (measured as the difference between the saturated water vapour concentrations at the temperature of fog formation and the dawn temperature) was very poor. This is thought to result from the variability of fog drop size distributions for a given liquid water content and from the unknown amount of dew associated with the Fog.

For the Wagga Wagga cases studied, the mean difference between the dew point temperature at fog clearance and formation was $3.7^{\circ}C$ with a standard error of $2.2^{\circ}C$. Such mean data should be useful for predicting fog clearance temperatures where radiosonde data is not available.

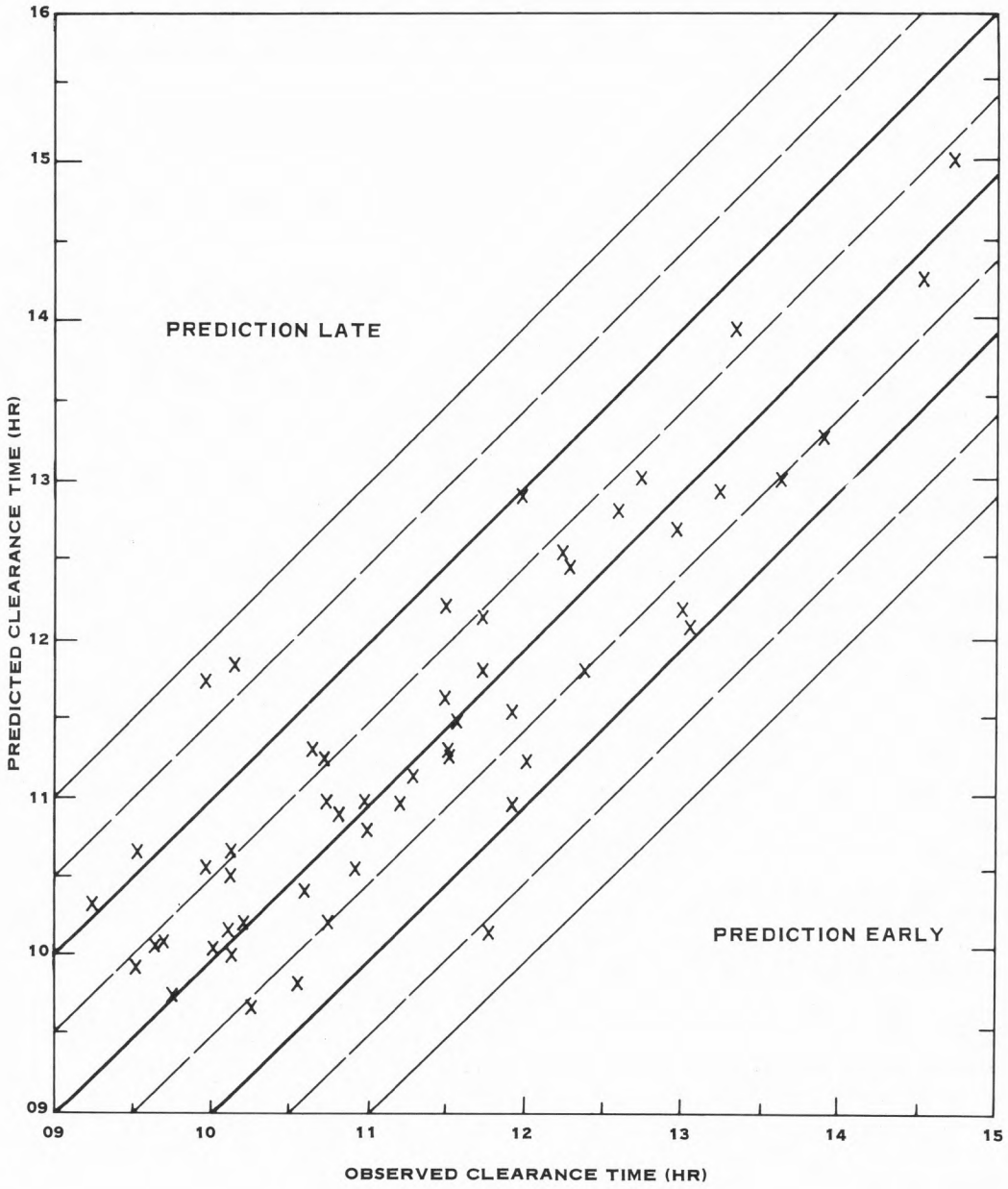


Fig 5 The predicted clearance times based on radiosonde data for 54 cases of fog at Wagga Wagga, New South Wales plotted against the observed clearance times. All times are true solar time.

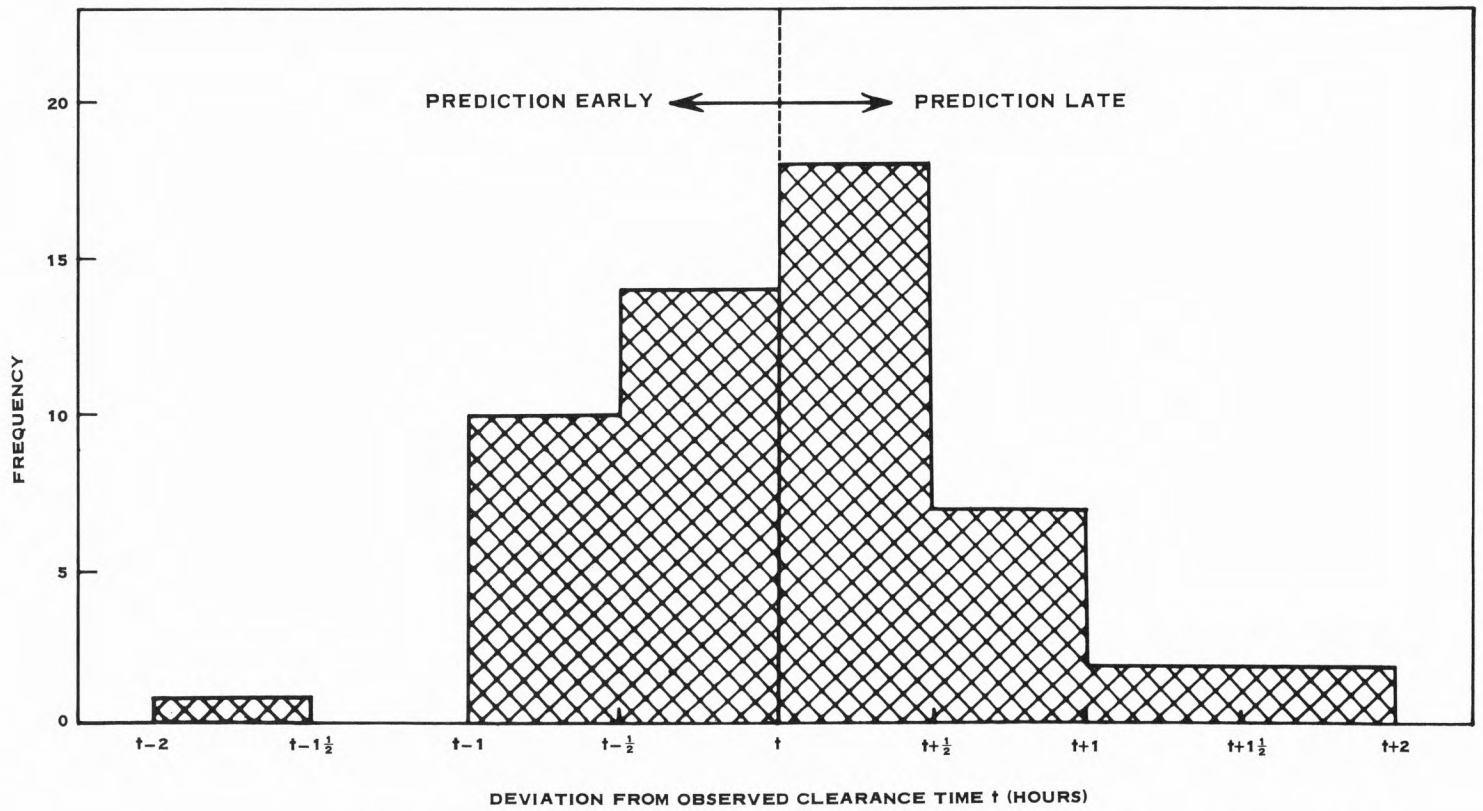


Fig 6 Histogram showing the frequency distribution of the difference between predicted and observed clearance times (hr) for the Wagga Wagga data of Fig 5.

(c) Canberra

For Canberra, nine fog cases were obtained for 1972 with temperature profile information. The predicted and observed clearance times are shown in Table 4 for the 9 cases obtained. The mean prediction time was 1 hour late with a standard deviation about the mean of 45 minutes.

Atkins (1965) found it necessary to correct his predicted times by adding 2 hours due to local effects. Subtracting 1 hour from the predicted times would considerably improve the fit of the Canberra data although a larger number of case studies would be required to verify this type of correction. One possible explanation for this correction is that heat from the city of Canberra may make a significant contribution to fog clearance. Another explanation is that the altitude of Canberra reduces radiation absorption in the atmosphere resulting in an increase in direct beam insolation by comparison with a sea level site. The zenith absorption of the atmosphere for solar radiation at the height of Canberra would be about 93% of that at sea level, assuming a uniform distribution of absorption in the atmosphere. Thus a zenith transmissivity of 62% at sea level would be effectively 66% at the height of Canberra, resulting in an increase in direct beam insolation and an increase in radiant energies available over and above the values of Table 2. Further investigation is required to determine whether Table 2 requires revision for elevated sites or whether an empirical correction to clearance time will suffice but this is beyond the scope of the present paper.

Table 4 Results of fog clearance predictions for Canberra. Times are given in True Solar Time.

Date	Predicted Clearance Time	Observed Clearance Time	Predicted-Observed
1-6-72	1000	0900	+1.00
8-6-72	1200	1000	+2.00
9-6-72	1030	0830	+2.00
19-6-72	1110	1000	+1.10
20-6-72	1140	1030	+1.20
28-6-72	1050	0930	+1.20
24-7-72	1105	1100	+0.05
4-8-72	1150	1100	+0.50
21-8-72	1100	1130	-0.30

CONCLUSIONS

The radiant energies I(t) available to clear a fog (Tables 2 and 3) are most accurate for the typical values of J, R, D and B as discussed previously. Variations of any of these quantities from their typical values will result in changed amounts of radiant energies available and thus in inaccuracies in the predicted fog clearance times. The radiant fluxes with the greatest influences on I(t) are J which varies with atmospheric transmission and R which varies with fog drop-size distribution. In addition, for the hours immediately after sunrise, D and B are of similar importance to J and R. This suggests that the prediction accuracy will be least just after sunrise and improve with fog duration, as suggested by Fig 5. Some improvement in prediction accuracy should be obtainable by increasing the number of variables in Eq 1. However as actual fog clearance takes place over about an hour for a particular site (or longer for neighbouring sites within a few miles), the improvement in prediction accuracy would not be marked in practical situations.

From the 20 and 54 cases of fog clearance prediction for Laverton and Wagga Wagga respectively, we may conclude that the radiant energy tables calculated for latitudes 40^{o}S and 35^{o}S are sufficiently accurate to enable computations of radiation fog clearance times to be made with a standard error in the prediction of about 40 minutes using radiosonde data. This compares favourably with results obtained in the northern hemisphere by others who used the insolation tables from Kennington (1961) at 50^{o}N. Cases where fog clears by advection or mixing will not be predicted using the scheme outlined. However few of these were found in the fog days studied for these two stations.

The prediction times for Canberra appeared to be too late by about 1 hour. As the sample of 9 cases was rather small, no firm conclusion about the usefulness of this scheme could be drawn for Canberra. However if further cases confirm the correction of 1 hour, reasonable accuracy should be obtainable there.

Fog clearance prediction trials (Atkins, 1965; Heffer, 1965; Kagawa, 1967, *etc*) using Kennington (1961) and suitable climatological estimators of fog clearance temperature and height result in standard errors of about 40 minutes. This suggests that similar accuracy should be attainable for

Australian stations, using Table 1, 2 or 3, where suitable climatological estimators have been developed. For example, fog height may be estimated for a particular station from vertical visibility or brightness or from the time elapsed since the fog first formed. The clearance temperature could be estimated as the dew point temperature at fog formation increased by a constant amount which would need to be determined for the particular site. It is suggested that the development of suitable climatological estimators should be performed locally for any stations where the fog forecasting scheme outlined is of sufficient use to justify the effort.

A knowledge of the temperature structure through the fog enables the greatest prediction accuracy to be obtained. At stations where fog is a serious problem there are often no radiosonde flights made or they are made too late for the fog clearance to be predicted. Wet and dry bulb temperature sensors, mounted beneath a tethered balloon would enable an accurate temperature profile to be obtained near dawn, suitable for predicting fog clearance time. Alternatively the mounting of a dry bulb temperature sensor and the photoelectric sensor described by Wright and Weinman (1967) would give the temperature profile and fog height with sufficient accuracy and also the presence or absence of a higher cloud layer. If it is not possible to obtain these observations for each fog, then estimates of clearance temperature and fog depth will be required based on the climatology of the particular site. The accuracy of this method varies from station to station and depends on how closely fogs at the station conform to an average temperature structure.

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